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TEST FIRE SIGNATURES AND THE FIRE-EMULATOR/DETECTOR-EVALUATOR

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Abstract

Existing methods for evaluating the performance of smoke and thermal detectors are reviewed. The levels of combustion gases, smoke, temperature and velocity likely to be produced in the European standard detector test fires are discussed, and this information is used to establish the operating conditions for a fire-emulator/detector-evaluator (FE/DE). The first-generation FE/DE being developed by BFRL will handle multi-criteria spot-type detectors over the anticipated range of realistic operating conditions. Measurements in non-flaming test fires (TF 2 and TF 3) are described and example signatures are proposed for training the FE/DE to evaluate combination smoke/heat/gas detection systems.

Background

Accepted test methods exist for the current generation of smoke and thermal detectors. The methods can be categorized as either synthetic or actual full-scale simulations. Full-scale simulations involve the placement of the detector in a large room [about 11 m long by 7 m wide and 3 to 4 m high in the Underwriters Laboratory[1] and the European[2] tests] and measuring the detector's response to a variety of actual small fires. These include flammable liquids, flaming wood cribs, burning plastics, and smoldering wood, cotton and newspaper. The UL test has the detector located near the ceiling and 5.4 m from the fire centerline. The CEN 54 test places the detector 3 m from the centerline of the fire.

The synthetic simulations take place in smaller chambers designed to duplicate either the smoke or heat produced during a fire. One of these, the Underwriters Laboratory smoke box[1,3], is about 1.7 m long, 0.5 m wide and 0.5 m high. A circulating fan with a straightening section is used to provide a uniform, laminar flow with air speeds between 0.16 and 0.76 m/s. A second UL chamber (0.30 m x 0.34 m x 0.61 m) is used to evaluate the sensitivity of the smoke detector to changes in velocity. In this test, a smoldering cotton wick is placed at different locations below the detector with a counterflow of air in the range of 0.16 m/s to 1.52 m/s.

European standard CEN 54, part 7[4] describes a procedure for synthesizing a controlled smoke environment to test ionization and optical detectors. A paraffin oil aerosol is introduced to a closed circuit wind tunnel with a 0.38 m square cross-section and a 0.75 m to 1.75 m long measuring zone. Air speeds are maintained between 0.1 m/s and 1 m/s, and the aerosol is polydisperse with the dominant area-weighted diameter being between 0.5 μm and 1.0 μm. Different designs exist for aerosol generators (e.g., refs. 5 and 6). Provision is made to test the detector at ambient temperatures, and for temperatures increasing from 20 °C to 50 °C at a rate of 1 °C/min. Air speeds are up to 10 m/s.

The performance of heat detectors is evaluated according to UL 521[7] and UL 539[8] in synthetic environments consisting of a temperature controlled oven and a 0.8 m x 0.25 m x 0.4 m chamber with 1.2 m/s air flow. Temperature gradients can be set to greater than 7 °C/min to test rate-of-rise detectors. Sprinkler-type thermal sensors are also evaluated full-scale, in a large room 18 m on a side and 4.8 m high. A burning 1.7 m^2 pool of ethanol provides the source of heat.

Open or closed circuit wind tunnels are specified in CEN 54, parts 5, 6, and 8, for testing the different types of thermal detectors.[9-11] The key parameters synthesized are the air velocity (0.8 m/s ± 0.1 m/s @ 25 °C), the maximum heating rate (30 °C/min), and the maximum temperature (170 °C). The accuracy on control of temperature measured 0.23 m upstream of the detector is specified to be within 2 °C.

Test fires such as those used in the UL and CEN standards have only been partially characterized. Pfister[12] measured the H_2, CO_2, CO and total hydrocarbon levels at the ceiling above the center of the CEN flaming wood fire (TF 1), the pyrolyzing wood fire (TF 2), the smoldering cotton fire (TF 3), the UL 217 smoldering paper fire, and an overheated transformer. The response of radiation, ionization, light scattering and thermal detectors to these fires was also recorded. Jackson and Robins[13] sampled the plume gases 3 m off the centerline near the ceiling in all six CEN test fires. They quantified the temperature, CO and H_2 mole fractions, relative humidity, and oxygen depletion. Smoke levels were monitored with optical and ionization detectors. Cleary and co-workers[14, 15] focused on the pyrolyzing wood fire (TF 2) and the smoldering cotton fire (TF 3). Their measurements are summarized later in this paper.

Attributes of a Fire-emulator/detector-evaluator

Existing test fixtures emulate a number of important aspects of actual fires, but each is limited to single-element detectors that respond either to smoke or heat. Ideally, detector evaluation should be independent of the detector operating principle, and many characteristics of an early fire should be duplicated simultaneously during the evaluation. The concept for a more universal fire emulator was introduced by Grosshandler[16, 17] for the purpose of providing a well-controlled environment into which fire sensors could be exposed to highly reproducible, time-varying concentrations of combustion products at predetermined temperatures and flow velocities. A properly designed fire-emulator/detector-evaluator (FE/DE) would have distinct advantages over existing detector test methods. These include the following:

- Test-to-test variations would be minimized.
- Single element gas, smoke, and thermal sensors, as well as multi-criteria detectors, could be evaluated under identical conditions.
- Line-type detectors, new combinations of existing sensors, and novel devices operating on new principles all could be accommodated.
- The emission of noxious combustion gases and the precautions necessary for live-fire tests could be minimized.

Table 1 lists the different types of detectors that one may want to evaluate in a FE/DE. Included are point (or spot) detectors that sense heat or the composition of combustion products (with single or multiple sensing elements); detectors that sense the state of the environment along a line (e.g., contiguous temperature sensitive wires) or through an open path (e.g., laser light attenuation across a room); and volume detectors that respond to portions of the electromagnetic or acoustic field (e.g., uv flame detectors). Across the top of the table are different fire conditions that need to be emulated. These include various fuels and ignition sources, smoldering combustion, deflagrations and detonations. A "0" indicates that a particular combination of emulator/detector already exists. For example, methods have been established to evaluate single-element temperature detectors in constant pressure flames (i.e., deflagrations) for burning liquids and solids, or for smoke detectors exposed to smoldering solids.

Number "1" symbolizes a detector/fire scenario that will be emulated in the first generation FE/DE. This encompasses single-element point detectors that sense combustion gases, combination multi-element detectors, and line detectors exposed to smoldering and flaming combustion. A second generation emulator (FE/DE II) will be required to properly assess volume-detectors and some line-type detectors. These and their applications are noted with a "2". Version III ("3" in Table 1) is proposed to be aimed at ignition and pre-detonation events, sensed by fast response volume- and line-detectors, and must have the capability to withstand explosions. Some combinations of sensing systems will require

Table 1. Fire-emulator/detector-evaluator fire applications matrix

Detector Evaluated	Ignition			Smolder Wave (heat source or self-sustained)	Deflagration (gas, liq., sol.)	Detonation	
	spark	hot surf.	flame			gas	aerosol
Point single-elem., gas:							
CO, CO_2, H_2O, O_2	--	--	--	1	1	0,3	--
NO_x, HCs, CH_4, H_2	--	--	--	1	1	0,3	--
HCl, HF, HCN, SO_x	--	--	--	1	1	--	--
Point single-elem., particle:							
smoke < 100 nm	--	--	--	0,1	0,1	--	--
smoke > 100 nm	--	--	--	0,1	0,1	--	--
fuel aerosols	--	--	--	1	--	--	3
Point single-elem., therm.:							
temperature	--	--	--	0,1	0,1	--	--
heat flux	--	--	--	0,1	0,1	--	--
Point multi-elem., combi.	--	--	--	1	1	3	3
Line-detector, contiguous:							
gas	--	--	--	1,2	1,2	3	--
temperature	--	--	--	1,2	1,2	--	--
Line-detector, open-path:							
gas	--	--	3	1,2	1,2	--	--
aerosol	--	--	3	1,2	1,2	3	3
temperature	--	--	3	1,2	1,2	--	--
pressure	3	--	3	1,2	1,2	3	3
radiation	3	3	3	1,2	1,2	3	3
Volume-detector:							
narrow-band uv/vis/ir	0,2,3	0,2,3	0,2,3	0,2	0,2	0,3	0,3
broadband	0,2,3	0,2,3	0,2,3	0,2	0,2	0,3	0,3
sonic pressure	2,3	--	2,3	2,4	2,4	0,3	0,3
ultra-sonic	--	4	--	4	4	3	3
Combination (pt./line/vol.)	2,3,4	2,3,4	2,3,4	2,4	2,4	3,4	3,4

Notes:
0. emulation and/or evaluation procedure already exists
1. version I of FE/DE
2. version II of FE/DE (open plume, vol. detectors)
3. version III of FE/DE (explosion proof, fast response det.)
4. customized evaluation required

-- does not apply

customized testing/certification facilities, as indicated by a "4". No number ("--") in the table signifies that a given detector is inappropriate for a given fire threat (e.g., a point smoke detector is unable to sense a spark quickly enough to warn of a pending detonation event, and a sonic pressure detector is unsuited for sensing a hot surface just prior to ignition).

A similar matrix, shown in Table 2, can be generated for nuisance signals. The detectors are identical to the ones listed in Table 1. Different sources of non-fire signals include the gases, aerosols, and heat which are produced during cooking or from operating combustion engines; natural fogs and dust suspensions; consumer products such as cleaning fluids and solvents (prevaporized and in aerosol form); radiation across the entire electromagnetic spectrum; and mechanical disturbances (e.g., vibrations, dirt, insects, pressure fluctuations). Currently, there are no generally accepted procedures for evaluating the susceptibility of a fire detector to non-fire signals (hence, no "0" entries in Table 2). The boxes marked with a "1" have been targeted for emulation in FE/DE I. The numbers 2, 3 and 4 have the same meaning as in Table 1. Note that stray high energy and stray very long wavelength electromagnetic radiation and mechanical disturbances require custom fixtures (marked "4" in table) and will not be emulated; however, the influence of uv, visible and ir radiation on triggering false alarms in open-path fire detectors could be attempted.

Operating Parameters for FE/DE

A range of some of the conditions to which a fire detector is likely to be exposed can be gleaned from previous measurements in test fires and from the sensitivity levels specified in the current UL and CEN standards. The velocity, temperature, gas composition, smoke levels, and radiation are discussed in the following paragraphs.

Velocity Field: The normal air velocities in the vicinity of a point detector are small, often below 0.5 m/s. Directly over a thermal plume the velocity can exceed 2 m/s, and near a ventilation duct or an open window wind speeds over 5 m/s would not be uncommon. The FE/DE should, therefore, be able to control the mean air flow between 0.5 m/s and 5 m/s.

The transport of combustion products into a detector and the response of a line-type sensor may be influenced by the scale and intensity of the turbulence as well as the average free-stream velocity. These parameters are small in near-laminar flows. Turbulence intensities between 3% and 20% may be encountered in turbulent buoyant jets and duct flows. The turbulence scale for a given flow is distributed between small, isotropic fluctuations (less than a millimeter) and scales of the order of the size of dominant objects within the structure (tens of centimeters). No data exist on the actual turbulence parameters likely to be encountered by detectors in the field, in either a fire or non-fire situation. Different size wire meshes can be used to generate small scale turbulence; and large eddies can be generated by placing bluff bodies in the free stream within the FE/DE ahead of the detector location.

Temperature Field: From the measurements of Jackson and Robins[13], one knows the peak temperatures at the detector location in the CEN 54 fires. These vary between 1 °C above the ambient for the smoldering wood and cotton fires (TF2 and TF3) and 58 °C above the ambient for TF5, the flaming heptane pool. The maximum rates of temperature change measured were between 0.1 °C/min and 30 °C/min. In order to accommodate the current generation of thermally released sprinkler heads, the ideal FE/DE needs to produce air temperatures up to 170 °C.

Data have not been reported on the temperature fluctuations adjacent to the detector in either the CEN 54 or UL test procedures. For conventional, slow-reacting heat sensors the value of the fluctuation is not important. For miniature heat sensors with a short response time, however, the temperature spectrum could provide useful information. It is unlikely that frequencies faster than 0.5 Hz will be emulated in the first generation FE/DE.

Gas Composition: The concentrations of some of the gaseous products formed in small test fires have been reported in the literature[12, 13]. Maximum deviations from ambient conditions attained at the detector site were in the range of thousands of parts per million by volume of CO_2, H_2O and O_2; hundreds of ppmv for CO; and tens of ppmv for H_2. Non-zero values of hydrocarbon species, acid

Table 2. Fire-emulator/detector-evaluator nuisance applications matrix

Detector Evaluated	Cooking, Engine Exhaust			Natural Aerosols		Consumer Products		Electromagnetic Radiation		Mechanical Disturb.
	gas	part.	heat	dust	water	gas	part.	x-ray, γ-ray, RF	uv, ir vis.	obstruct., vib., press.
Point single-elem., gas:										
CO, CO_2, H_2O, O_2	1	--	--	--	1	1	--	4	--	4
NO_x, HCs, CH_4, H_2	1	--	--	--	--	1	--	4	--	4
HCl, HF, HCN, SO_x	1	--	--	--	--	1	--	4	--	4
Point single-elem., part.:										
smoke < 100 nm	--	1	--	1	1	--	1	4	--	4
smoke > 100 nm	--	1	--	1	1	--	1	4	--	4
fuel aerosols	--	1	--	1	1	--	1	4	--	4
Pt. single-elem., thermal:										
temperature	--	--	1	--	--	--	--	4	--	4
heat flux	--	--	1	--	--	--	--	4	--	4
Point multi-elem. combinations	1	1	1	1	1	1	1	4	4	4
Line-det., contiguous:										
gas	1,2	--	--	--	1,2	1,2	--	4	4	4
temperature	--	--	1,2	--	--	--	--	4	--	4
Line-det., open-path:										
gas	1,2	--	1,2	1,2	1,2	1,2	1,2	4	1,2	4
aerosol	--	1,2	--	1,2	1,2	--	1,2	4	1,2	4
temperature	--	--	1,2	--	--	--	--	4	1,2	4
pressure	1,2	--	1,2	--	--	--	--	4	--	4
radiation	--	--	1,2	1,2	1,2	--	1,2	4	1,2	4
Volume-detector:										
narrow-band, uv/vis/ir	2	2	2	2	2	2	2	4	2	4
broadband	2	2	2	2	2	2	2	4	2	4
sonic pressure	--	--	2	--	--	--	--	4	--	4
ultra-sonic	--	--	--	--	--	--	--	4	--	4
Combination (pt./line/vol.)	2,4	2,4	2,4	2,4	2,4	2,4	2,4	4	2,4	4

Note: See table 1 for explanation of numbers.

gases, and NO are undoubtedly present and are just now being quantified[14, 15] in standard fires used to evaluate detector response.

As a minimum, the first generation FE/DE should be capable of emulating the build-up of CO_2, CO, and H_2O as measured. The magnitude of the turbulent concentration fluctuations is unknown and would be difficult to simulate. Minor species like H_2, CH_4, and higher/oxygenated hydrocarbons could be added in a straight forward manner once enough data have been accumulated from actual test fires. Acid gases and noxious species such as NO, HBr, HCl, HF, HCN, and SO_2 could cause operational problems if present in too high a concentration, but at low levels diluted in N_2 they could also be injected into the FE/DE in a controlled manner. This would be necessary if the choice of fuels is broadened to include substances like PVC, nylon and fire retarded materials.

Particulate Matter: Many studies have been undertaken on the properties of condensed matter formed in fires (i.e, smoke). To properly describe particulate matter requires knowledge of its chemical composition, size distribution, number density, and morphology. Because soot invariably is not chemically equilibrated with its gaseous surroundings, satisfactory means to predict the quantity or attributes of solid material produced in real fires do not exist.

Current methods for evaluating fire detectors recognize two qualitatively different kinds of smoke: soot formed during short residence times in flaming fires, and aerosols formed during pyrolysis and in smoldering fires. The maximum values of extinction coefficient measured by Jackson and Robins[13] range from 0.03 m^{-1} for the flaming ethanol fire (TF 6) to 0.69 m^{-1} for the smoldering cotton. The precise character of these smokes has not been measured in test fire settings. Instead, the industry has relied on the response of standard smoke detectors to characterize the particulate emissions, operating on either the ionizing radiation or scattered light principle. In contrast, the detailed composition, concentration and morphology of soot formed in a number of simple laboratory burners have been well documented (e.g., refs. 18-20). Similar detailed measurements are required in the plume above the test fires to verify that the concept of two types of smoke ("gray" and "black") is sufficient to evaluate detectors that may operate on different principles.

Smoke is emulated by misting paraffin oil in the CEN 54 fire simulation apparatus. Methods to control droplet size and number density have been developed for some of these tests. The index of refraction and morphology of particles formed during pyrolysis and smoldering fires may be duplicated reasonably by this approach; however, the imaginary part of the index of refraction is much higher for particles formed in flames, rendering the paraffin less than satisfactory for emulating flaming fire smoke.

The ideal FE/DE would produce on demand a fire aerosol with specified composition, size distribution, number density and morphology. A match of these properties would guarantee the appropriate index of refraction. Control of all these attributes of smoke in the FE/DE is well beyond the current state-of-technology. A combination of smoke generators operating on different principles may be required.

Electromagnetic Radiation: Smoldering fires emit thermal radiation associated with hot smoke particles and pyrolysis gases. Small flaming fires emit radiation from the ultraviolet through the infrared. A large number of commercial flame and spark detectors are on the market that operate on the basis of sensing one or more portions of the electromagnetic spectrum. Radiation travels in all directions from the source and reflects from surfaces in the volume being protected, making the performance of a flame detector highly dependent upon the geometry of the room. Thus, a fire emulator that is satisfactory for detectors of gas, heat or smoke at one point may be unsuited for detectors of radiation which monitor the entire room volume.

A heated, black surface would yield a continuous source of visible and infrared radiation, and a small methane flame would reproduce the UV due to chemiluminescence and the infrared bands associated with hot water vapor and CO_2. It would be necessary to vary in a tightly controlled manner the temperature and solid angle of the radiation sources as viewed from the detector location. The fluctuating radiation signals, which characterize flickering flames, would also need to be controlled.

Nuisance electromagnetic radiation can result from any portion of the spectrum. Properly emulating the viewing angle would also apply here. False sources of UV can be traced to solar radiation, lightning, fluorescent lights, welding operations, and sparks from electrical machinery. Interior lighting and solar radiation are large sources of visible radiation, and hot surfaces such as exhaust manifolds or space heaters emit strongly in the infrared. Although it is conceivable that a universal facility could be designed to accommodate each of these nuisance sources, the first generation FE/DE will not include this capability. False electrical signals can be generated if the detector or processing electronics are exposed to RF, x-rays or γ-rays of sufficient intensity. A separate chamber specifically designed to control these extra long and extra short wavelengths is necessary and will not be a part of the FE/DE.

Nuisance Aerosols: The procedures developed to emulate the velocity, temperature, and concentration fields of actual test fires in the FE/DE could be adapted easily to yield the environment produced by non-fire sources of false alarms such as extreme temperatures, wind, excess CO from automobile exhausts, volatile liquids, or space heaters. The aerosols generated by non-fire sources, however, require special attention. A powder generator similar to that used to seed LDA gas flows could prove useful for emulating nonorganic dusts or pollen. Household chemicals and cooking aerosols could be dispensed in the same manner as the paraffin oil soot emulator. The charring of food could be simulated by placing specimens on a small electric hot plate or under a radiant "broiler". The concentration levels of the nuisance aerosol around the fire detector and the rate at which they build must bracket the conditions most likely to be encountered by the detector in the field. Too little is known about these conditions to specify them for the first generation FE/DE.

Table 3 is a summary of the conditions to be emulated in the first version FE/DE. The maximum design velocity is limited to 2.5 m/s even though higher flows are conceivable. However, this value most likely exceeds the velocities attained at the detector location in current test fires and is more than twice the value specified in existing UL and CEN simulators. The blower will be selected large enough to allow higher velocities by limiting the temperature increase or by reducing the test section area. The maximum temperature observed in the field and shown in the table (170 °C) refers to the current limit imposed for sprinkler activation testing. By limiting the FE/DE to a maximum of 100 °C one loses the capability to reproduce Parts 5, 6 and 8 of CEN 54. This is not thought to be critical, however, since 100 °C is well above the temperature where a fire detector should respond, and is a warmer environment than most would expect to be placed. A number of conditions are listed in Table 3 as "tbd" (to be determined) because measurements of these quantities have not been made with the precision necessary (if made at all) to bracket the dynamic range.

Components of the FE/DE

Figure 1 is a block diagram showing the major components of the proposed FE/DE-I facility. The detector will be located in the test section, which is designed to handle single-point, multi-point, and line-type detection systems. Upstream of the test section is the smoke and particle injection system. Care will be taken to minimize the loss of aerosol mass to the walls of the emulator. The gases (N_2, CO_2, CO, H_2 and CH_4) will mix uniformly into the airstream prior to the addition of the particulate matter. A separate gas generator will be used to produce water vapor. The heater and blower are located, in order, upstream of the mixing section. Both will use programmable closed-loop feedback control from precision temperature and velocity sensors located in the test section.

The detector/evaluator test section will be 0.9 m wide by 0.3m high. A length of 4 m has been chosen to allow enough room for a ceiling boundary layer to develop and also to provide space for the evaluation of different types of line detectors. There will be provision for point detectors to be tested in vertical and horizontal orientations. Access ports will allow measurement of the composition, temperature, and velocity to ensure that the fire signature is properly emulated at the location of the detector.

The major combustion gases will be stored in two cylinders pressurized with nitrogen. Programmable mass flow controllers will meter the appropriate amount of gas to a tubular ring injector. It is proposed that water vapor be generated in a methane burner and routed to the center of the duct.

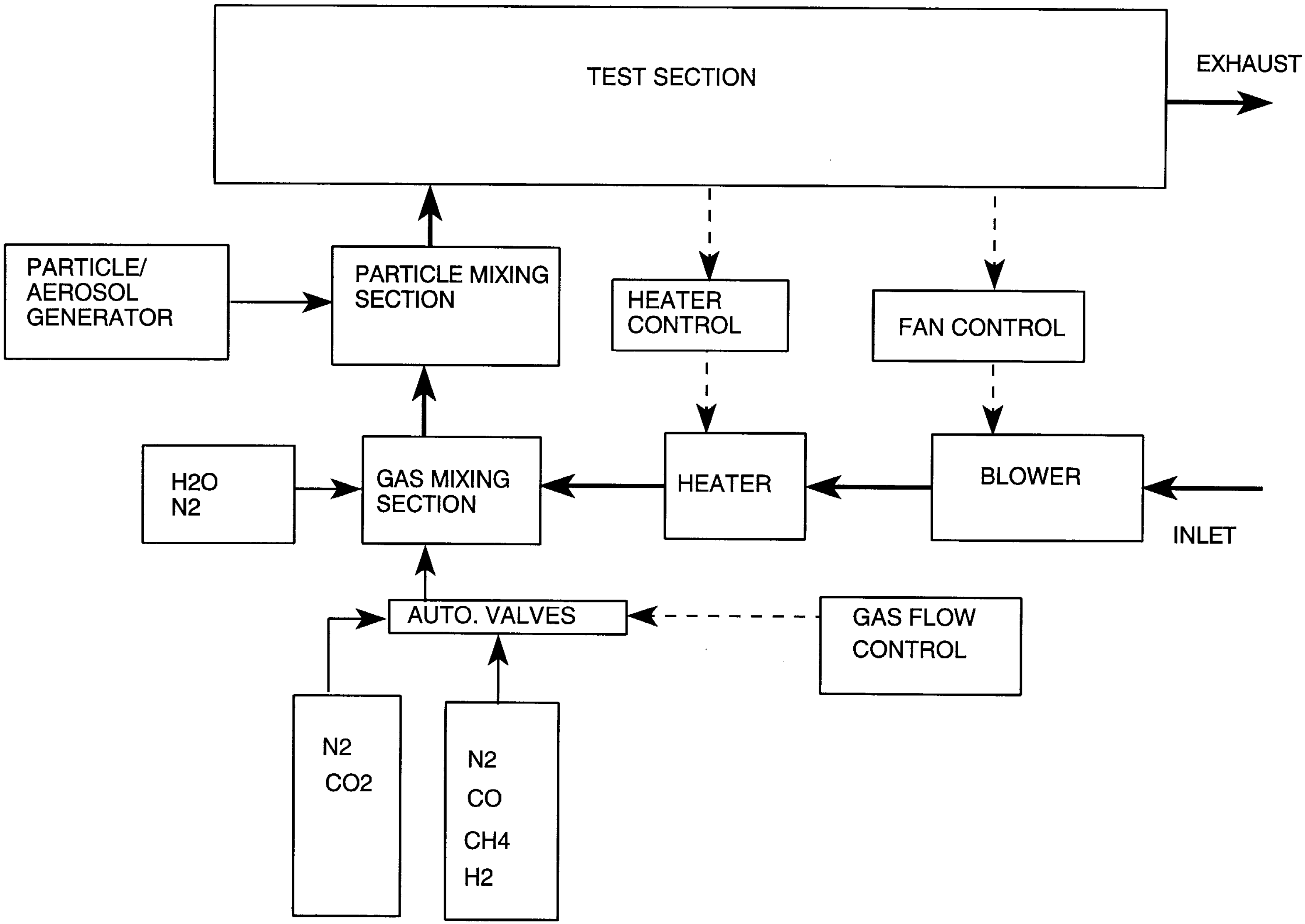

Figure 1. Block diagram of fire-emulator/detector-evaluator, version I (FE/DE-I)

Table 3. Dynamic range of fire characteristics emulated in FE/DE-I

Parameter	Observed in Field	Range in FE/DE	Max Gradient	RMS Deviation	Fluctuation Frequency
Velocity	0.5 to 5 m/s	0.5 to 2.5 m/s	0.1 m/s^2	2 to 10 %	0.1 to 1000 Hz
Temperature	-30 to 170 °C	25 to 100 °C	30 °C/min	uncontrolled	< 0.5 Hz
ΔCO_2 10^{-6} vol. fraction	0 to 12,000	0 to 12,000	120/s	uncontrolled	< 0.1 Hz
ΔH_2O 10^{-6} vol. fraction	0 to 12,000	0 to 12,000	120/s	uncontrolled	< 0.1 Hz
ΔO_2 10^{-6} vol. fraction	0 to -12,000	0 to -12,000	-120/s	uncontrolled	< 0.1 Hz
CO 10^{-6} vol. fraction	0 to 400	0 to 400	10/s	uncontrolled	uncontrolled
H_2 10^{-6} vol. fraction	0 to 70	0 to 70	10/s	uncontrolled	uncontrolled
CH_4 10^{-6} vol. fraction	unknown	0 to 200	10/s	uncontrolled	uncontrolled
oxygenated or higher hydrocarbons	unknown	tbd*	tbd	uncontrolled	uncontrolled
HCl, NO	unknown	tbd	tbd	uncontrolled	uncontrolled
particulate extinction coeff.	0 to 0.7 m^{-1}	0 to 0.7 m^{-1}	.01 m^{-1}/s	uncontrolled	uncontrolled
IR radiation	unknown	tbd	tbd	tbd	0 to 20 Hz

*to be determined

Liquid water could be sprayed through a hollow-cone pressure jet nozzle into methane combustion products, producing a maximum ratio of H_2O to CO_2 estimated to be 17:1.

Nine annular-shaped resistance heaters, 5 kW each, will be placed in series to control the air temperature. The outer diameter and total length of the heater will be 0.5 m and 0.69 m, respectively. Power to the heater will be provided by a programmable, 160 A control panel. The blower will be a direct drive tubeaxial fan with a 1 kW motor, capable of moving over 1100 L/s through a pressure drop of 350 Pa.

Details of the smoke generator have not yet been developed. One concept is to use a rich, premixed propene/air burner to generate smoke in an attempt to emulate a plastic or liquid fuel fire. Nitrogen gas would be used to transport the soot to the 0.3 m by 0.3 m square duct. The concentration of soot in the nitrogen would be varied by adjusting the flame equivalence ratio and fuel flow rate. The total flow to the emulator duct would be controlled by regulating the bypass valve. Smoldering and pyrolyzing smoke would be formed in a radiant heated chamber into which a controlled amount of nitrogen and air would flow. A bypass system similar to the one used with the propene/air burner would be used to adjust the total flow to the duct. A yet-to-be-designed fluidized bed system would be used to deliver non-flame solid particulate matter. Each of the three aerosol producing systems would be characterized before installation to ascertain the exact nature of the particles and how it changes with operating conditions.

Signatures from Smoldering/Pyrolyzing Fires for "Training" Emulator

Two of the test fires described in CEN 54[2], TF 2 and TF 3, involve smoldering materials. An electric heater is used to char wood in TF 2. Power is supplied continuously up to the point of flaming, which typically occurs more than 10 minutes into the test. A self-sustained smoldering cotton wick is used in TF 3. The data presented here are from measurements in the plume close to the fuel source. A schematic of the test room is shown in Fig. 2; Fig. 3 is a sketch of the gas sampling system. Details of the experimental facility and instrumentation are described elsewhere[14]. The primary objective of these measurements was to quantify the source of important chemical species and particulate matter, the plume momentum, and the thermal energy provided by the fire. This information can be used to specify the source terms of hydrodynamic models of the actual space to be protected, which in turn dictate the conditions to be emulated in the FE/DE for evaluating a detecting system sited in the room.

Smoldering Wood (TF 2): Beechwood blocks with a total mass between 121 g to 127 g were placed uniformly around two concentric circles on top of a 0.22 m diameter electrical hot plate. The test began by initially applying 1.9 kW of power to the hot plate. The temperature on the surface of the hot plate reached 600 °C in 490 s $\pm$ 15 s for the five different runs, which was well within the time limit specified in CEN 54. Mass loss became perceptible about 20 s into the test. The peak pyrolysis rate was 0.26 g/s $\pm$ 0.01 g/s, occurring 620 s $\pm$ 10 s after heating began. Figure 4 is a plot of the mass loss rate for each test. The repeatability for the first 720 s is remarkable considering that the loss rate is computed from the gradient of the instantaneous mass of fuel measured by the load cell. The wood eventually burst into flames (creating the spikes in Fig. 4), but always after at least 70% of the mass had been lost.

The plume temperatures, averaged over multiple runs, 0.88 m above the hot plate, are plotted in Fig. 5. The centerline temperature reaches 45 °C in 660 s, and decreases with increasing radius in all directions. Velocities at the same axial position peaked at slightly over 1.0 m/s on the centerline. The volume fractions of CO_2, CO and H_2O measured on the hot plate centerline were reported by Cleary[14, 15]. The ratio of CO to CO_2 was approximately constant at 1/3 throughout the heating period. The water was released from the wood much sooner, but reached its maximum volume fraction (0.45 %) at about the same point in time. The total hydrocarbon levels were measured with a flame ionization detector, while methane, acetaldehyde, and acetic acid were found from line-of-sight FTIR analysis. Laser extinction through the plume, 0.22 m above the smoldering wood, was measured and showed good repeatability. Assuming Beer's law held, the extinction coefficient at 633 nm averaged across the plume diameter was found to be about 10 m^{-1}.

Smoldering Cotton (TF 3): Six independent experiments were run using the smoldering cotton fires. Figure 6 shows the cumulative mass loss, normalized by the initial mass of fuel, for the different runs. The large variation in burning rates was attributable to the state of the wick material. A higher burning rate occurred if the wicks remained straight and in close contact with each other. If the individual wicks separated from one another and curled outward, more heat was lost to the environment and the chimney-like structure of the initial wick sample was destroyed, affecting the entrainment of oxygen into the smoldering zone. It is unclear which initial conditions led to the outward curling of the wicks.

The radial variations in temperature were examined 0.05 m above the top of the wick. The centermost temperatures were within 20 °C of the those measured half way to the edge of the fuel source. Temperatures at the edge rarely exceeded 40 °C, and were as much as 100 °C below the centerline values. This suggested a top-hat profile near the fuel surface with a high temperature uniform core increasing in time to about 120 °C and a close-to-ambient value at the edge of the fuel. The average temperatures measured with time on the fuel centerline 0.16 m above the top of the wicks (see Fig. 7) increased steadily for 650 s to about 70 °C, and thereafter increased at a slower rate to a maximum of 88 °C at 1500 s. Temperature excursions exceeding 100 °C can be seen in the run-to-run deviations.

The attenuation of laser intensity through the plume 0.01 m above the smoldering cotton wicks led to an estimated extinction coefficient (at 633 nm) 600 s into the test of 16 m^{-1} $\pm$ 6 m^{-1}. Measured values of the CO, CO_2 and H_2O are presented in the report by Cleary[15].

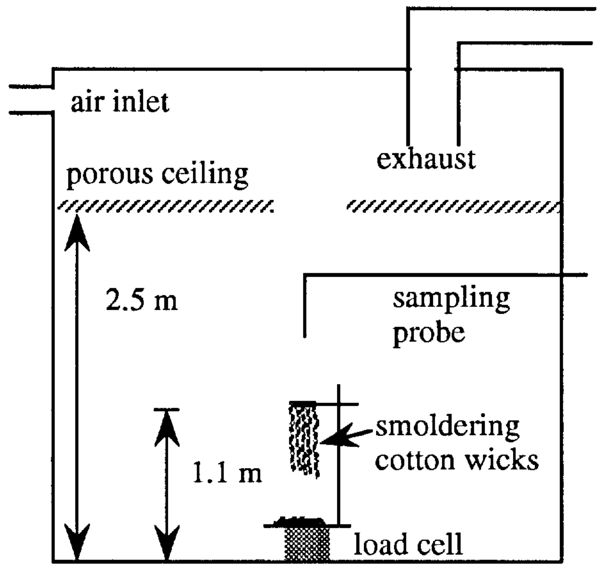

Figure 2. Schematic of detector fire test room (set up for TF 3).

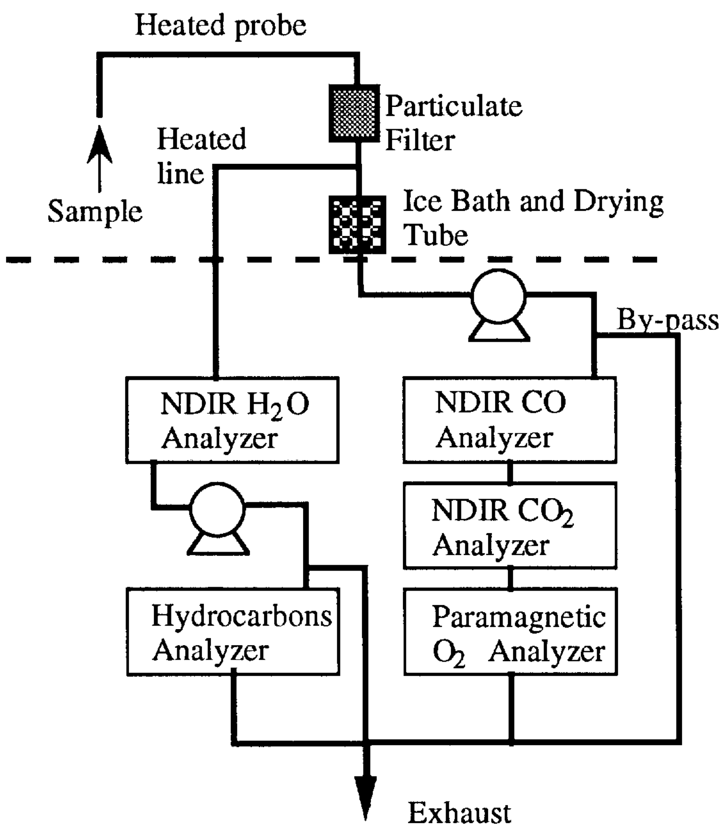

Figure 3. Block diagram of gas sampling system for test fire plume measurements.

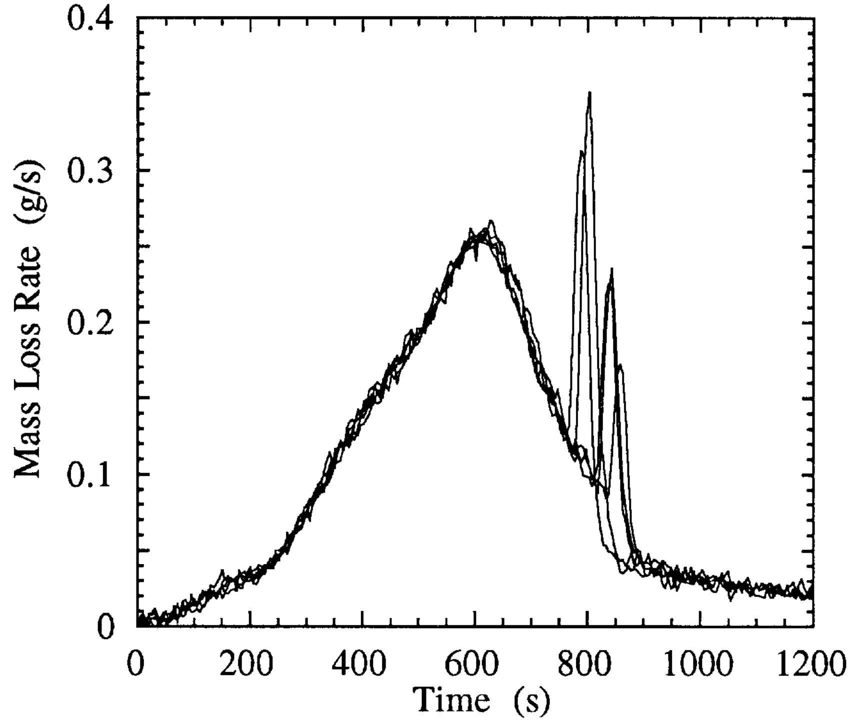

Figure 4. Composite mass loss rate of five charring wood tests (TF 2).

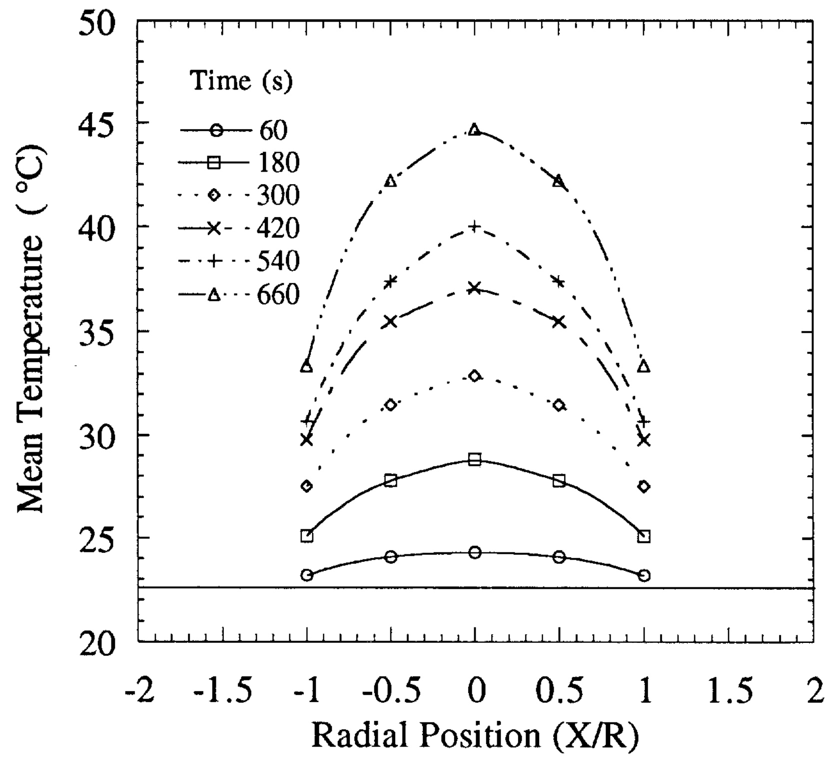

Figure 5. Radial temperature distribution as a function of time in plume 0.88 m above charring wood test fire.

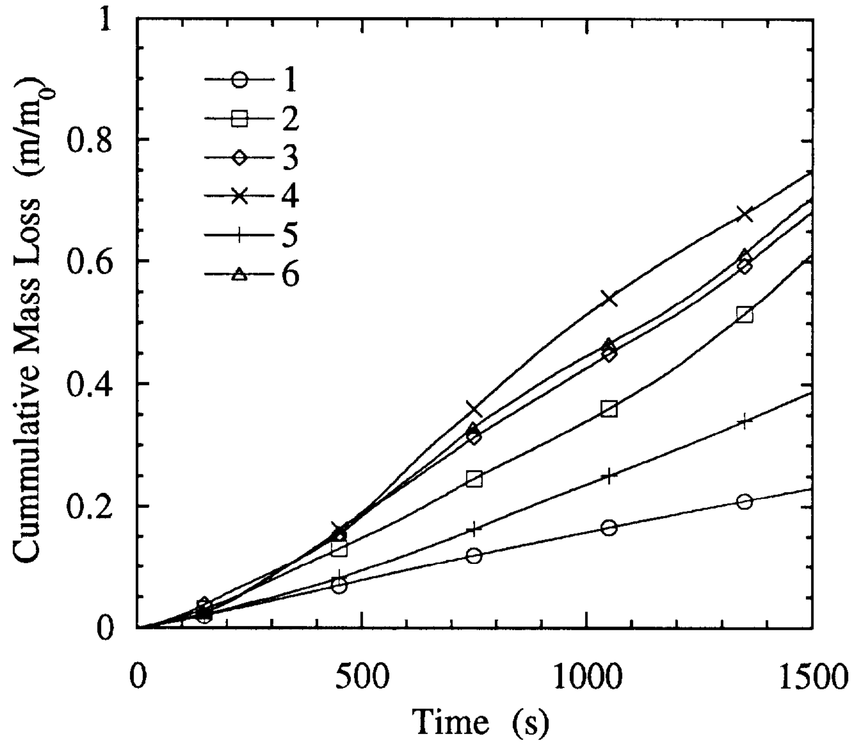

Figure 6. Mass loss from six smoldering cotton wick test fires (TF 3).

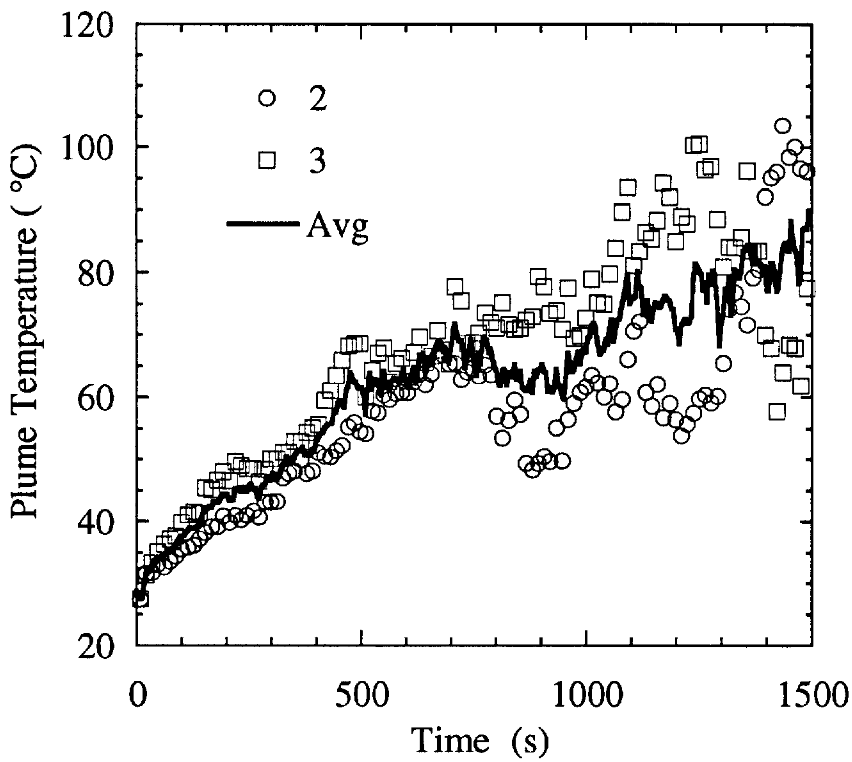

Figure 7. Plume centerline temperature 0.16 m above cotton wicks (TF 3).

Generic Signatures for TF 2 and TF 3: Pfister[12] and Jackson and Robins[13] measured the ceiling temperatures and combustion products in the TF 2 and TF 3 fires burning in a standard CEN 54 room. Their reported temperature increases and volume fractions of CO and CO_2 are 6 to 8 times lower than those measured here in the smoldering wood fire, 0.88 m above the hot plate. The hydrocarbon levels measured previously[12] are a factor of 60 times lower than those measured here, an inconsistency suggesting a possible sampling problem in the older study or a difference in operating procedure. Comparing the previous measurements taken near the ceiling in TF 3, the values of CO_2, CO and temperature increase measured 0.16 m above the cotton wick in the current study are greater by over an order of magnitude. Modeling of plume entrainment and the ceiling jet are required to ascertain if the different studies are in general agreement with each other.

Preliminary time signatures of temperature, velocity, H_2O, CO_2 and CO suggested for these two smoldering fires are plotted in Figs. 8 and 9. Note that they refer to predicted centerline values 0.88 m and 0.16 m above the TF 2 and TF 3 fires, respectively. As more testing is completed, additional species volume fractions (e.g., H_2, CH_4, NO) and electromagnetic spectra will be added to these signatures. The standard deviation and characteristic fluctuating frequencies will also be accumulated. With this information, computational fluid dynamics can be used to model the transport of heat and species throughout the CEN 54 test room or any other volume in need of protection. This modeling approach has been used in a number of situations to determine the impact of room geometry[21], distance from the fire[22], and room ventilation[23] on the likely response of a fire detector. The response of a multi-criteria detector to a smoldering fire can also be evaluated by exposing the sensors to the temperatures and concentrations predicted by the fluid mechanical models. The fire-emulator/detector-evaluator will be constructed expressly for this purpose. The data summarized in Figs. 6 and 7 are, thus, key to the successful implementation of the FE/DE concept.

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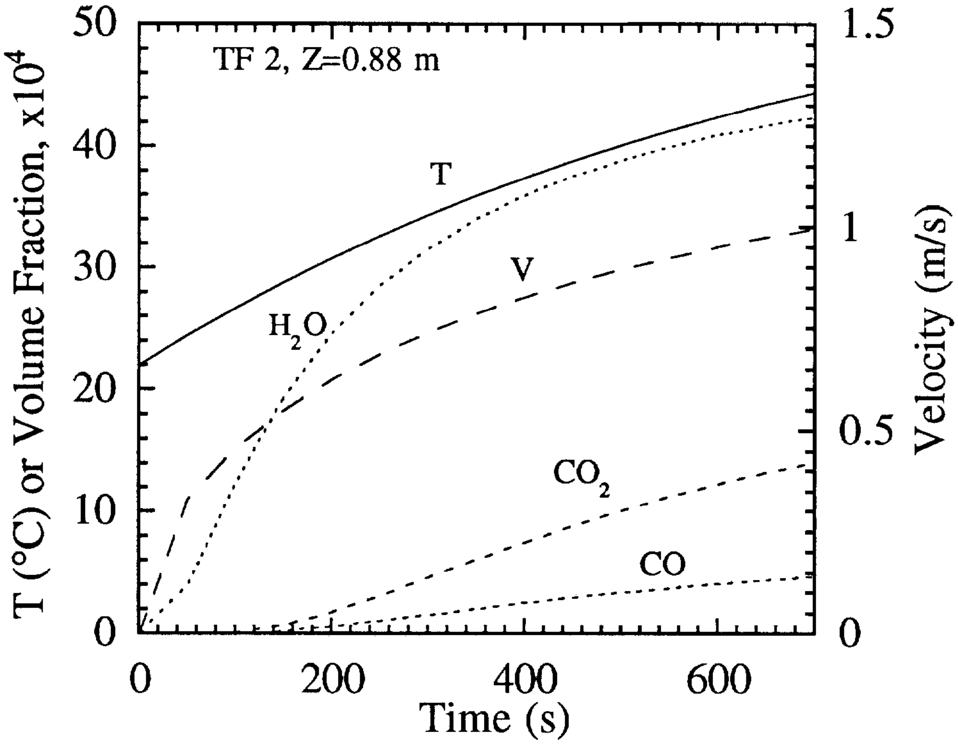

Figure 8. Generic signature for temperature, velocity and species on centerline 0.88 m above charring wood fire (TF 2).

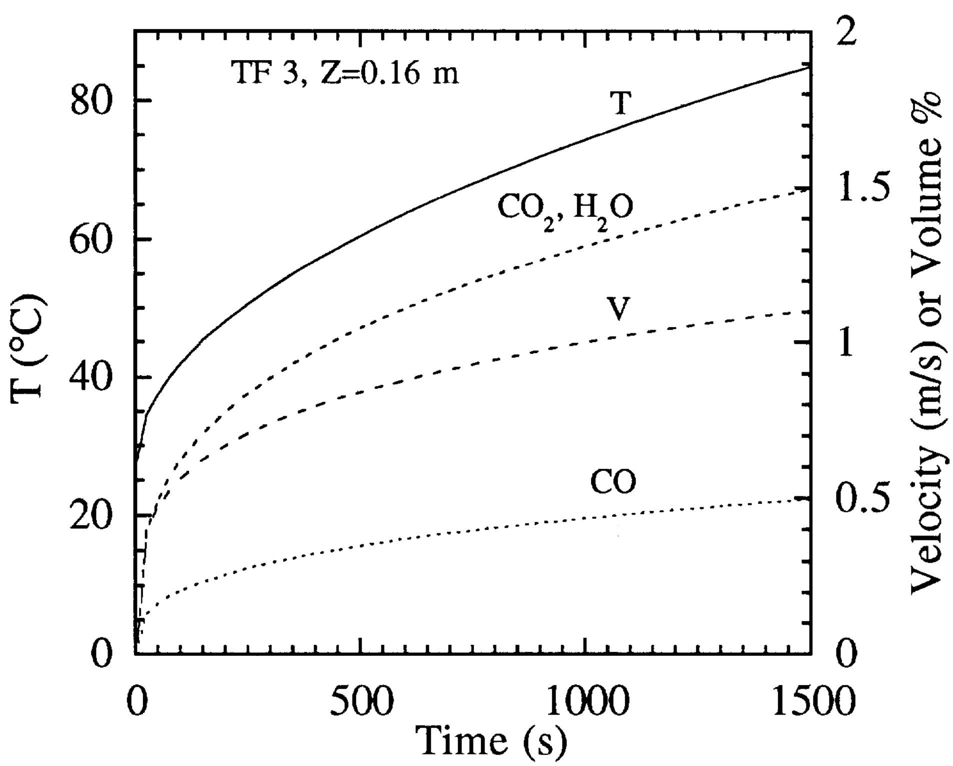

Figure 9. Generic signature for temperature, velocity and species on centerline 0.16 m above smoldering cotton wicks (TF 3).

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